# COORDINATED FLYING

Kenneth H Lau

Joseph R Guinn

New Millennium Autonomy IDPT

# Agenda

- Overview
- Vocabulary
- Coordinated Flying
- Coordinated Flying in Earth Orbit
- Coordinated Flying in Deep Space
- Testing Coordinated Flying
- Visions
- Acknowledgments
- Questions

# Overview - Why Coordinated Flying?

- Enabling for science inquiries requiring large baselines
  - Single structure configurations have practical limitations that may be mitigated by multi-spacecraft paradigm
    - Deployment, mass, size, other launch vehicle constraints
- Functional redundancy
  - Replenishment
- Lead to potential cost savings



K. Lau, J. Guinn, 2/9/96

# COORDINATED FLYING VOCABULARY

# Vocabulary Associated with Multiple Spacecraft

- Hierarchical specific vocabulary for coordinated spacecraft
  - Fleet
  - Constellation
  - Formation Flying
    - Coarse
    - Intermediate
    - Precision

- Definitions obtained from Merriam-Webster Collegiate Dictionary (http://c.gp.cs.cmu.edu:5103/prog/webster or http://www.eb.com:180/)

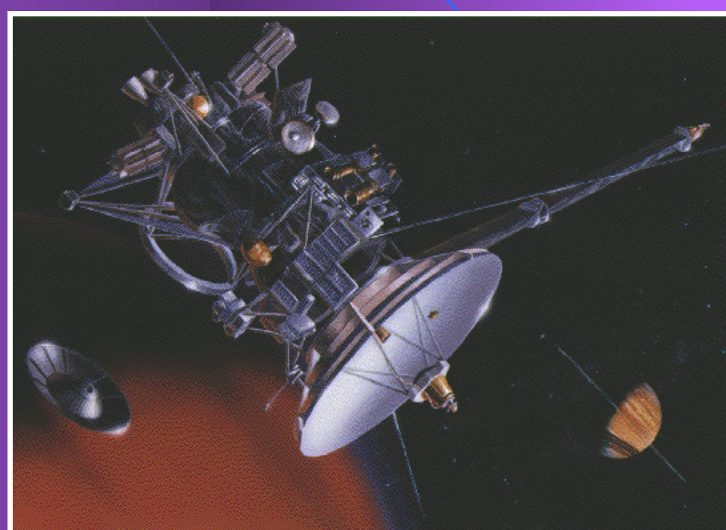
# Definition of Fleet

- 3. **fleet** n ***2: a group (as of ships, planes, or trucks) operated under unified control***

- A collection of spacecraft
  - Mixture of independent spacecraft and spacecraft in arrangements
  - Loosely related in function or high level mission while performing various specific missions and purposes
  - Multiple missions can include spacecraft that spans over various times
  - Geometric pattern not required

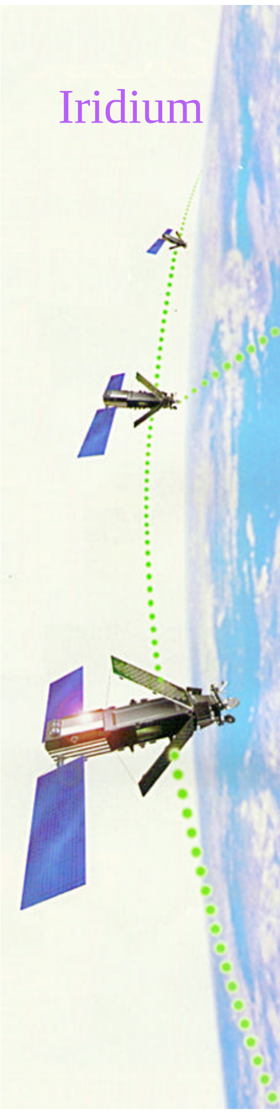
# Spacecraft Fleet Example

- Shuttle Fleet
- A collection of JPL deep space fleet that includes:
  - Rangers
  - Mariners
  - Surveyor
  - Viking
  - Voyagers
  - Magellan
  - Galileo
  - Mars Pathfinder
  - Cassini



# Definition of Constellation

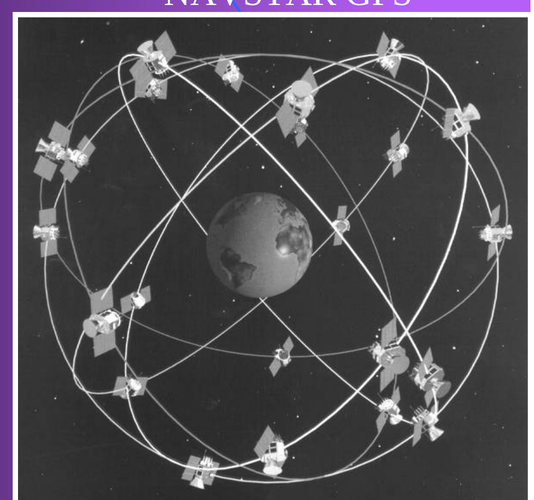
- **con.stel.la.tion** n *3: an assemblage, collection, or gathering of related persons, qualities, or things - 4 : pattern, arrangement*
- An assembly or collection of multiple spacecraft for a common purpose
  - In one or more orbital planes, usually symmetric, for earth orbiters
  - In a pattern or arrangement in deep space
  - Usually similar spacecraft
- "Open loop" arrangement control (current capability)
  - S/C may have no or limited capabilities for GN&C information cross linking (inter-spacecraft links) to control arrangement on-board
  - Controls typically generated by ground (e.g. maintain orbital plane and positions) or not at all
- Arrangements tend not to change significantly over moderate time scales




# Constellation Examples

- NAVSTAR Global Positioning System Satellites (24 satellites/6 planes)
- Constellation (formerly Aries) (48/4)
- ICO (formerly Inmarsat-P) (10/2)
- Teledesic (840/21)
- Globalstar (48/8)
- Odyssey (12/3)
- Iridium (66/6)
- Ellipso (10/2)
- NMP GPS Array (16/1-4)

NAVSTAR GPS



# Definition of Formation Flying

- **for.ma.tion** n ***6: an arrangement of a body or group of persons in some prescribed manner or for a particular purpose*** - for.ma.tion.al aj

- An assembly or collection of multiple spacecraft in an arrangement (orbit or pattern)
  - Coarse Formation Flying
    - Beginnings of “Closed loop,” loosely coupled arrangement control (current technology)
      - S/C have no or limited capabilities for GN&C information cross linking to control arrangement on-board
      - Arrangement may be controlled on board or from the ground
    - Coarse coordination control accuracy
      - Not separation distances or control knowledge
      - Accuracy measured in kilometers
      - Arrangements tend to change slowly over moderate time scales
    - Typically dissimilar S/C

# Definition of Formation Flying (con't)

- Intermediate Formation Flying
  - "Closed loop," moderately coupled arrangement control (current technology)
    - S/C have limited or full capabilities for GN&C information cross linking to control arrangement on-board
    - Real time ground control is challenging
  - Moderate coordination accuracy
    - Accuracy measured in meters
    - Arrangements and orientations tend to change moderately over time
  - Typically similar spacecraft

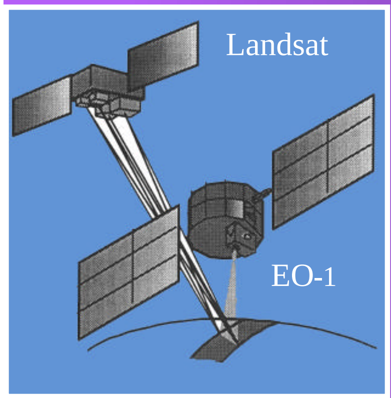

K. Lau, J. Guinn, 2/9/96

# Definition of Formation Flying (con't)

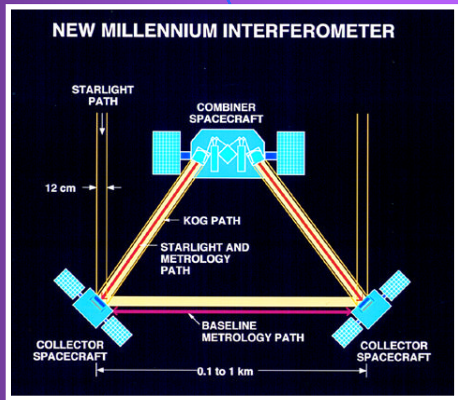
- Precision Formation Flying
  - "Closed loop," tightly coupled arrangement control
    - S/C have full capabilities for GN&C information cross linking to control arrangement on-board
    - Precision coordination accuracy
      - Accuracy measured in centimeters or better
      - Arrangements and orientations tend to change quickly over time
  - Typically identical spacecraft

# Summary of Formation Flying Definitions

| Class | Coupling | Control Accuracies | X-link | S/C Similarities | Ex. Sensors |
|---|---|---|---|---|---|
| Coarse | Loose | >1 km | No/limited | Not/limited | GPS/Others |
| Intermediate | Moderate | 1 m - 1 km | Moderate | Some | AFF/GPS |
| Precision | Tight | <1 m | Full | Fully | Optical/AFF |



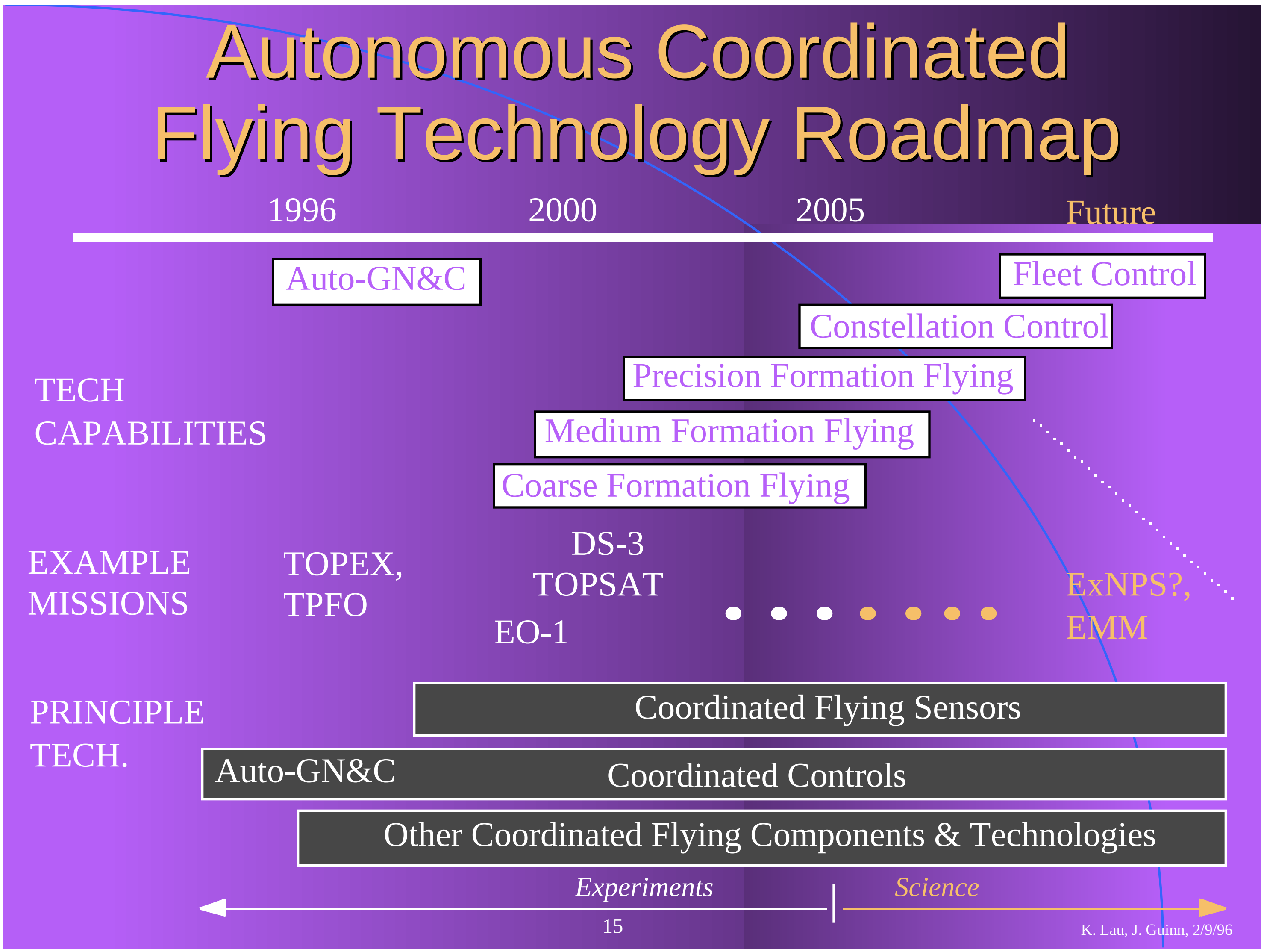

- New Millennium Earth Orbiting Mission 1: Land Imager (Coarse FF)
  - Accuracy measured in many kilometers
- New Millennium Deep Space Mission 3: New Millennium Interferometer (Precision FF)
  - Centimeter accuracy range






K. Lau, J. Guinn, 2/9/96

# COORDINATED FLYING



Autonomous Coordinated Flying Technology Roadmap
1996
2000
2005
Future
Auto-GN&C
Fleet Control
Constellation Control
Precision Formation Flying
Medium Formation Flying
Coarse Formation Flying
TECH CAPABILITIES
EXAMPLE MISSIONS
TOPEX, TPFO
DS-3
TOPSAT
EO-1
ExNPS?, EMM
PRINCIPLE TECH.
Coordinated Flying Sensors
Auto-GN&C
Coordinated Controls
Other Coordinated Flying Components & Technologies
*Experiments*
*Science*
15
K. Lau, J. Guinn, 2/9/96

# Coordinated Flying Challenges & Technologies

- Autonomous GN&C
- Autonomous formation controls
- Absolute &/or relative formation sensing between spacecraft
  - Position, velocity & attitude
- Inter-spacecraft information coordination
- Propulsion
- Mission operations

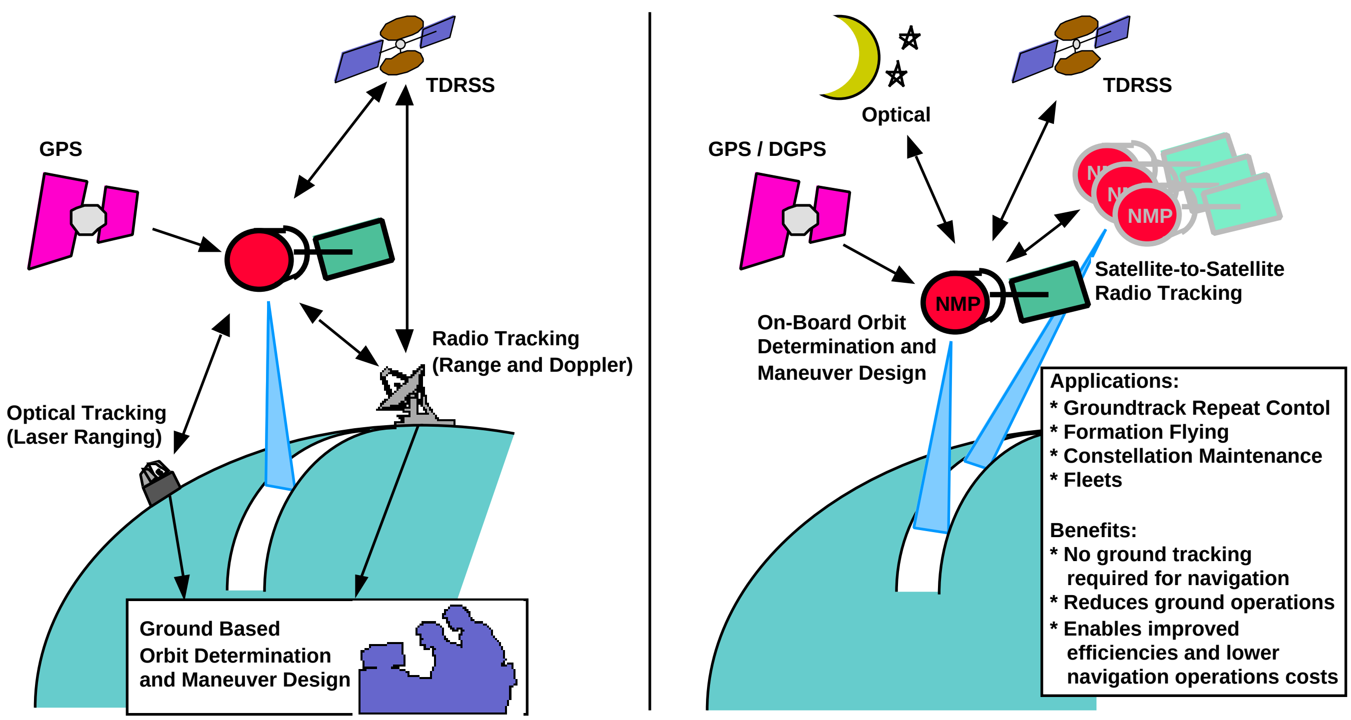
# COORDINATED FLYING IN EARTH ORBIT

Case Study: EO-1 Land Imager

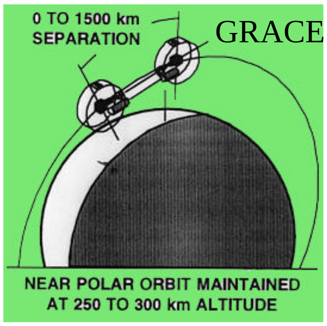
# Autonomous Earth Orbiter Navigation
## *Overview*

### CONVENTIONAL APPROACH

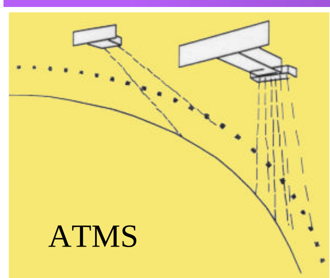
### AUTONOMOUS APPROACH



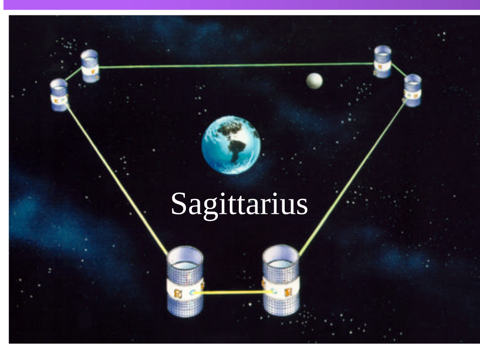

Joseph Guinn 2/9/96

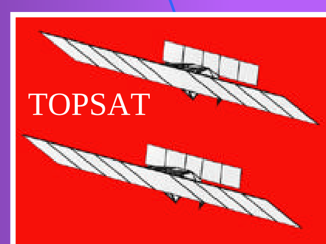



# Proposed EO Autonomous Formation Flying Missions




- Precision: relative control < 1meter
  - Currently Deep Space Only
- Intermediate: relative control 1m to 1km
  - TOPSAT (SAR & Laser Topography)
  - Sagittarius (Omega)
- Coarse: relative control > 1km
  - EO-1 (Land Imaging)
  - GRACE (Gravity Recovery & Atmospheric Change Experiment)
  - ATMS (Atmospheric Temperature & Moisture Sounding)

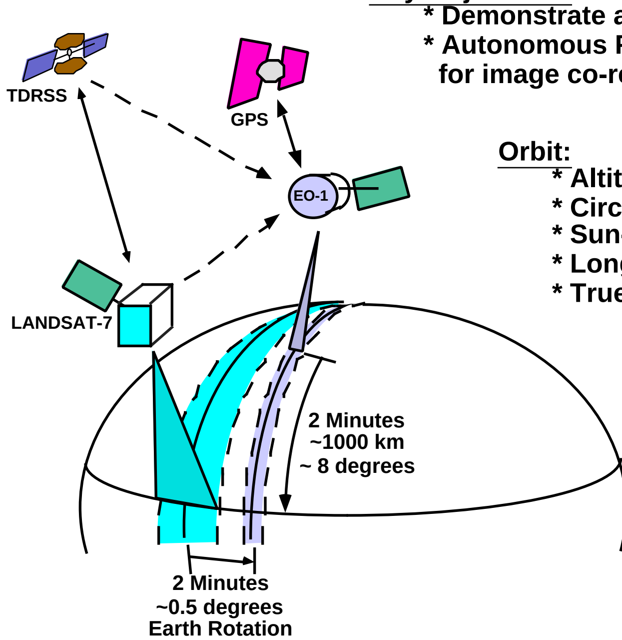





K. Lau, J. Guinn, 2/9/96

# New Millennium Program / Earth Orbit-1 Mission
## Mission Description



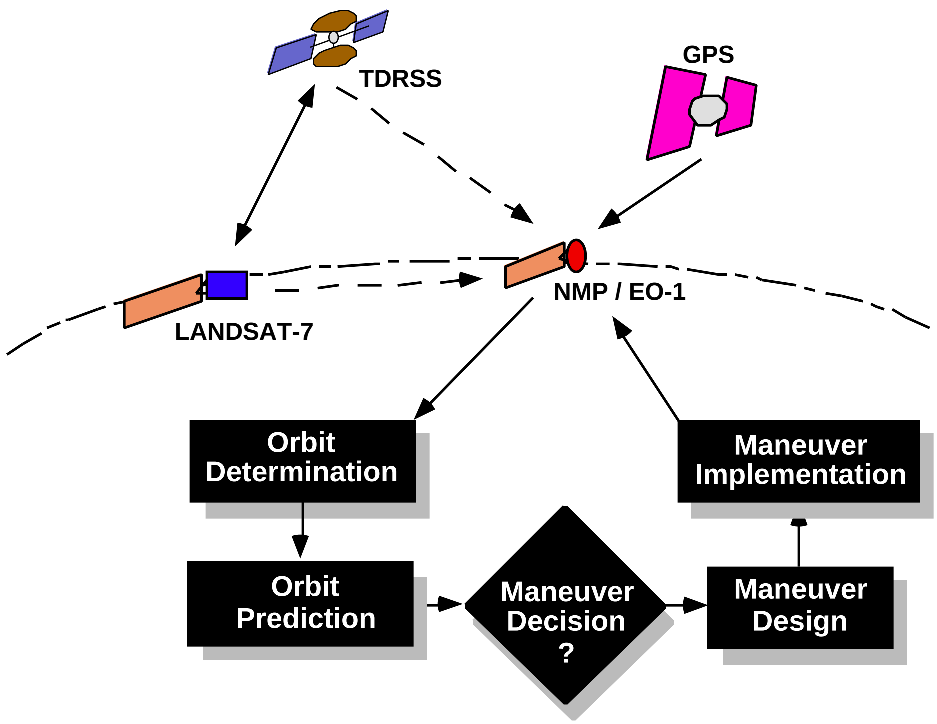

**Key Objectives:**
- * Demonstrate advanced land hyperspectral imager
- * Autonomous Formation flying with LANDSAT-7 for image co-registation/validation

**Orbit:**
- * Altitude = 705 km
- * Circular
- * Sun-synchronous, Inclination = 98.2°
- * Longitude of Ascending Node Offset 0.5°
- * True Anomaly Offset 8°

**Mission Parameters:**
- * Early 1999 Launch
- * Launch Vehicle LLV-1
- * Mission Duration 18 months

Joseph Guinn 2/9/96

# New Millennium Program / Earth Orbit-1 Mission
## Autonomous Navigation Elements




Joseph Guinn 2/9/96

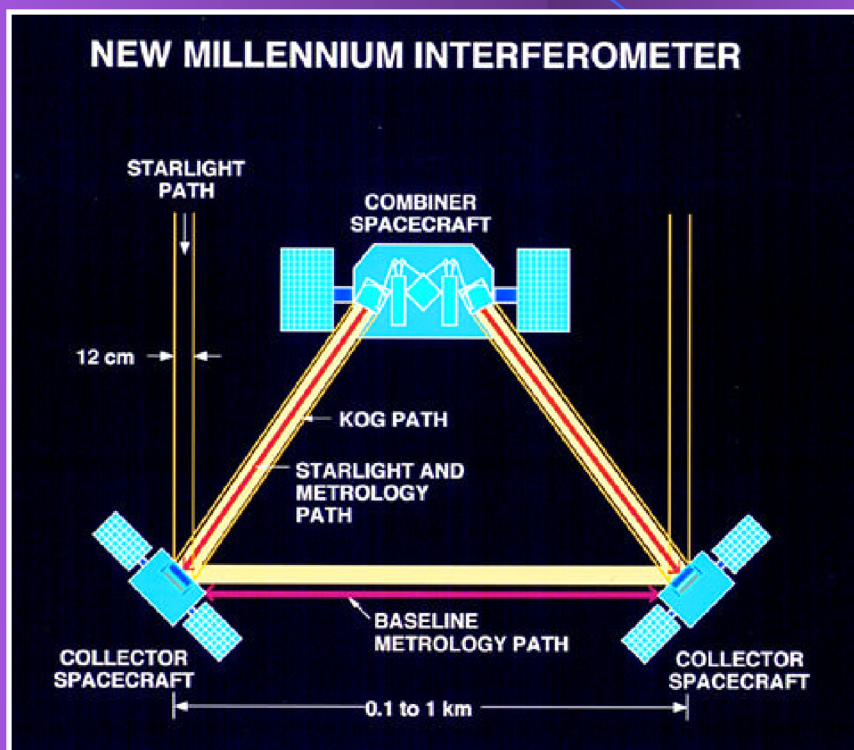
# COORDINATED FLYING IN DEEP SPACE

Case Study: DS-3 New Millennium Interferometer



K. Lau, J. Guinn, 2/9/96

# New Millennium Interferometer






K. Lau, J. Guinn, 2/9/96

# NMI Mission Description

- Heliocentric (SIRTF) orbit
  - ~0.1 Au away from Earth at the end of 6 months mission life
  - Navigation not essential
- Spacecraft approximately 1.7 m per side cubic
  - 3 axis stabilized
  - Body mounted solar array, always sun pointed
  - Approx. 150 kg wet mass per collector, 250 kg wet mass combiner
    - Approx. 16 kg wet mass - cold gas assumed presently



K. Lau, J. Guinn, 2/9/96

# NMI Special Requirements

- G&C
  - 100m to 1km baselines
    - ±1 cm relative ranging
    - ±1 arcminute relative orientation
    - ±0.1 mm/sec relative velocity measurements
  - Formation initialization and maintenance
  - Formation maneuvers
- Inter-spacecraft communications
  - Up to 500 kbits/sec
- Propulsion
  - Limited fuel mass
  - Perform potential large slews for formation initialization and imaging scenarios
  - Provide small thrust for formation maintenance

# NMI Challenges

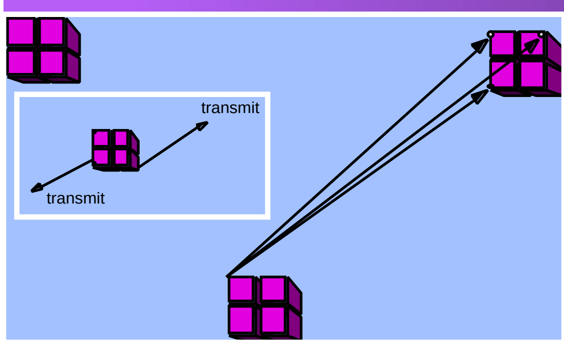
- Perform formation flying autonomously
  - Cannot control formation from ground operations
    - Initialization and maintenance
    - Optimize control architecture
    - Formation maneuvers
    - Collision avoidance
- Perform G&C sensing requirements with low mass, lower power, $4\pi$ steradian sensor(s)
- Perform Communications requirements with RF modem or radio ethernet
- Perform Propulsion requirements with small thrusters with high specific impulses
- Perform Mission Operations at large distances

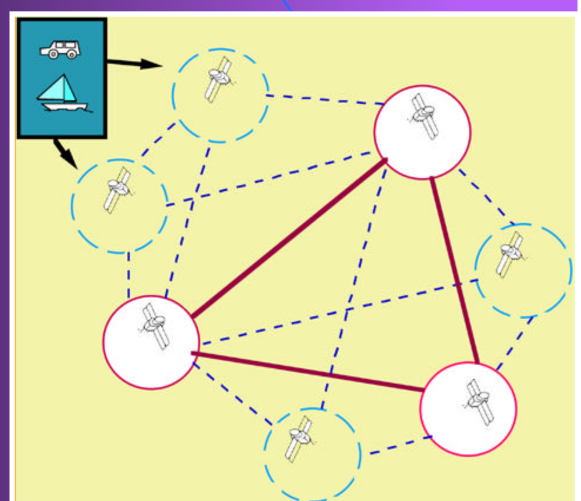
# NMI Technologies

- Autonomous formation flying controls
  - Formation initialization and maintenance
    - Initialize from a small cluster
    - Initialize from random distributed positions
    - Coordinated pointing
    - Maintain formation during maneuvers
    - Reconfigurability & adaptability
  - Controls architecture
    - Distributed or centralized
    - System-level fault isolation, recovery & prevention
  - Formation maneuvers
    - Dimensional changes
    - Rigid body rotations
    - Efficient interferometer maneuvers
      - Center of mass of formation
      - Pivot around S/C with least fuel
  - Collision avoidance
    - Avoid collisions upon separation from launcher
    - Avoid collisions during fault conditions

# NMI Technologies (con't)

- Formation Sensing
  - Autonomous formation flying GN&C sensor (AFF)
    - GPS ***trans***ceiver with attitude determination capabilities
      - Provide coarse formation ranges and attitudes (relative)
      - Does not use Earth's NAVSTAR GPS satellite signals for deep space
    - Multiple antennas will satisfy $4\pi$ steradian coverage desires
  - Kilometric Optical Gyro (KOG)
    - Laser gyro formed by 3 spacecraft
    - Provide rotation sensing for formation
  - Optical Metrology
    - Precision range sensor



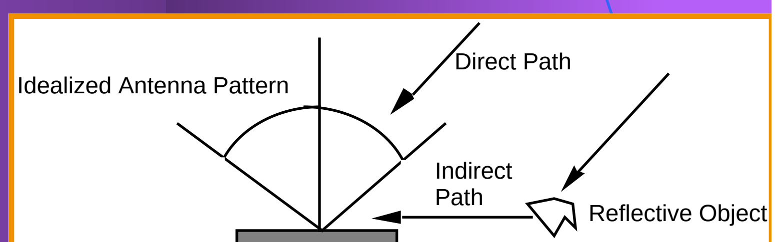





K. Lau, J. Guinn, 2/9/96

# NMI Technologies (con't)

- RF multipath elimination
  - Accuracy improvement for the AFF
    - Applicable for GPS receivers for Earth Orbiters
  - A promising new technique for GPS receivers based on "Seismic Deconvolution" recently developed
    - Capable of eliminating multipath down to receiver noise floor
    - Further investigation into using Deconvolution to lower noise floor





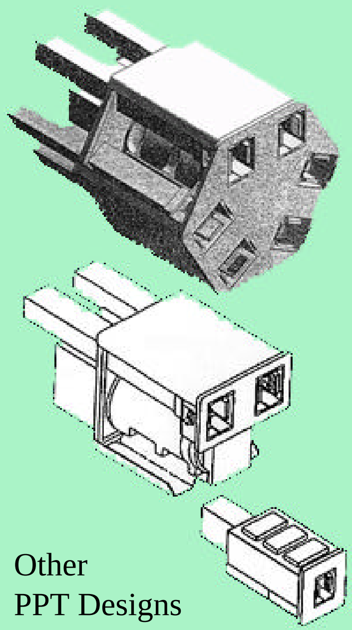

K. Lau, J. Guinn, 2/9/96

# NMI Technologies (con’t)

- Inter-spacecraft network information coordination
  - High data rate inter-spacecraft communications
    - RF modem/UHF transceivers
    - Radio ethernet
    - AFF
      - Encode onto AFF signals
  - High performance computing
  - Management of large parallel data sets

RF Modem

PCMIA RF Modem



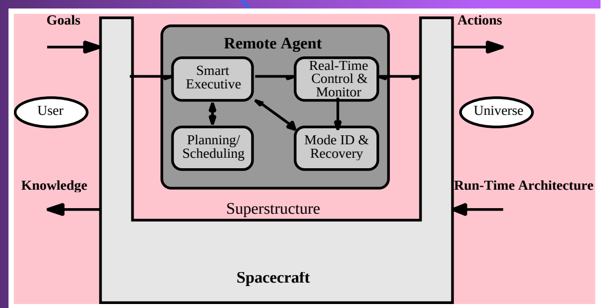
Other
PPT Designs


# NMI Technologies (con't)

- Small thrusters
  - 12 per NMI spacecraft baselined
  - Cold gas ($N_2$) thrusters baselined
    - Similar to those for Pluto Fast Flyby
      - 4.5 mN
    - Low $I_{sp}$
  - Pulse Plasma Thrusters (PPT)
    - 700 μN per pulse, up to 6 Hz
    - High $I_{sp}$
    - Requires higher power
    - Currently addressing contamination issues
      - Optical contamination
      - EMI/EMC

# NMI Technologies (con't)

- New paradigm in NMI Mission Operations: Autonomy Remote Agent
  - NMI mission operations cannot be performed through traditional methods
    - Large distances, in situ operations
  - Autonomy Remote Agent
      - Model driven behavior
      - Automatic reasoning
    - 3 components
      - Planning & Scheduling
        - Resource scheduling & constraint management without constraint violation
      - Smart Executive
        - Event-driven plan execution & run-time decision making for real-time response
      - Mode Identification Recovery
        - Deduce hidden states (failure) from sensors & plan recovery actions

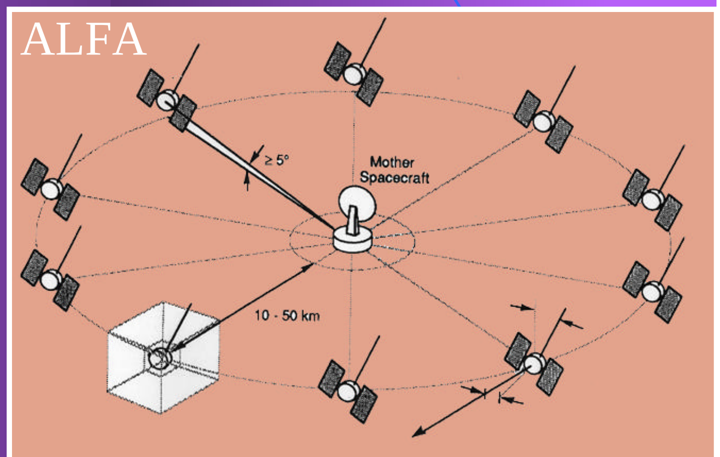





K. Lau, J. Guinn, 2/9/96

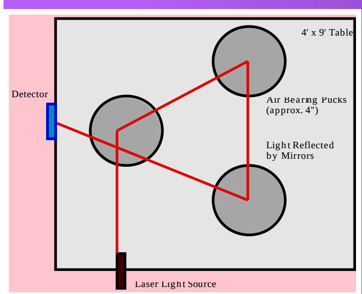
# Other Proposed DS Missions

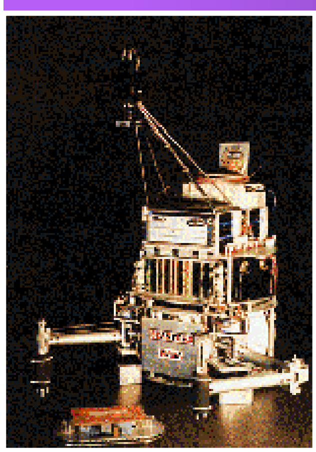
- Precision Formation Flying - accuracy measured in cm
  - MUSIC (Multiple Spacecraft Interferometer Constellation)
  - ExNPS (Exploration of Neighboring Planetary Systems)?
  - EMM (Earth Mapping Mission)
- Coarse Formation Flying - accuracy measured in km
  - ALFA (Astronomical Low Frequency Array)



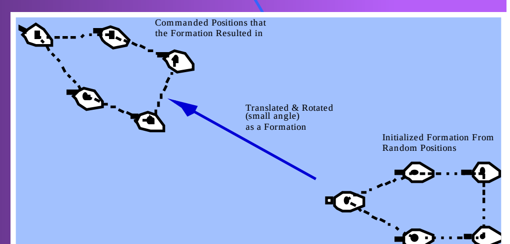
# TESTING COORDINATED FLYING

# Existing Coordinated Flying Testbeds

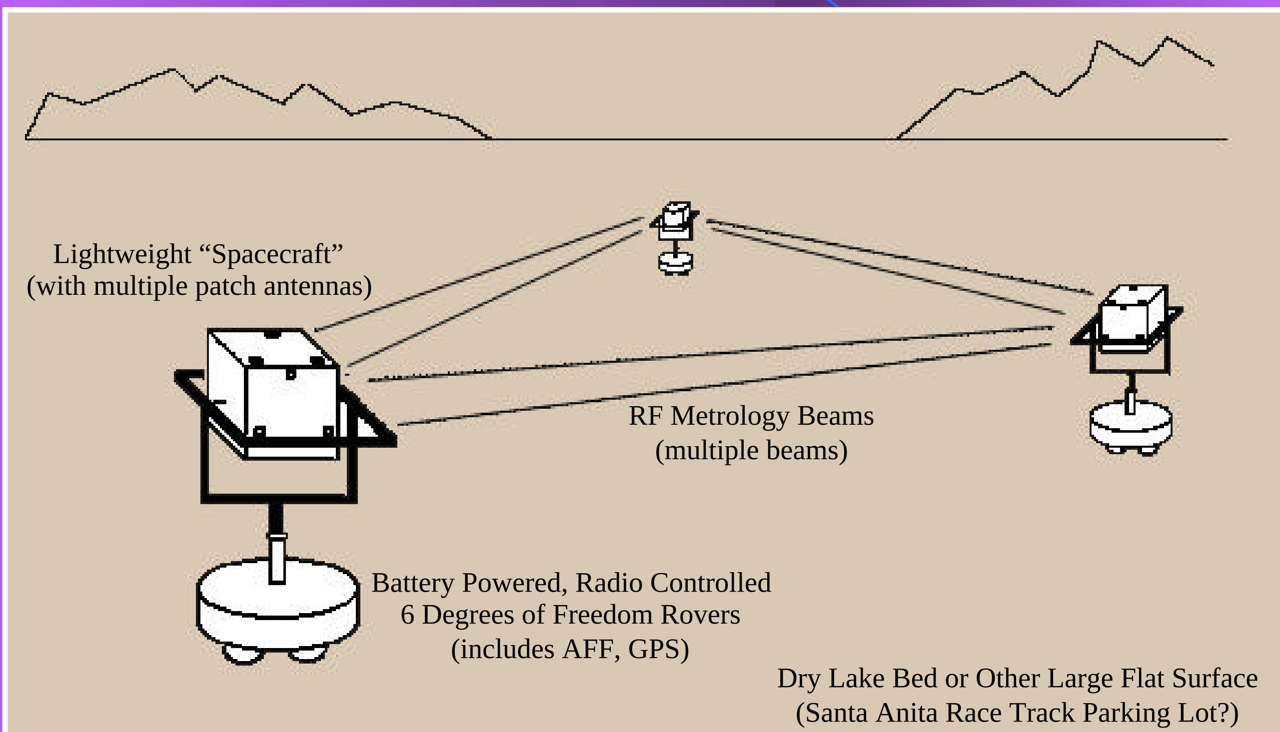


- Optically Linked Spacecraft Testbed
  - Dr. Fred Hadaegh, Dr. Randy Bartman & Prof. Paul Wang (UCLA)
  - JPL DRDF 1994
  - 3 small air bearing pucks with optical sensing capabilities
- Commotion Laboratory
  - Dr. Tony Lewis (UCLA)
  - Coordinated wheeled robots
- Stanford GPS Laboratory
  - Prof. Jonathan How (Stanford University)
  - 3 large air bearing vehicles with GPS sensing capabilities



# Proposed NM Formation Flying Testbed

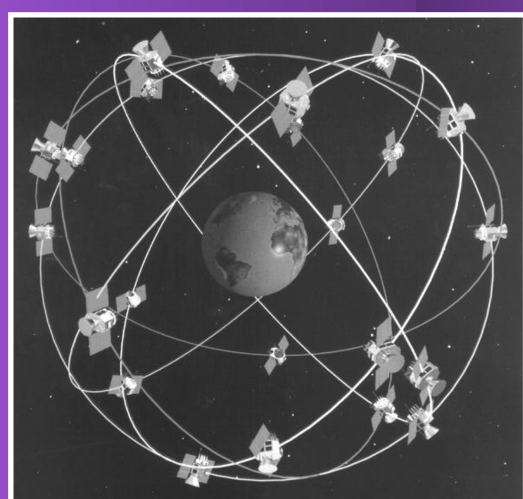





K. Lau, J. Guinn, 2/9/96

# VISIONS

- Autonomous Constellation control & operations
- Autonomous Fleet control & operations



# ACKNOWLEDGMENT


TEAM X
Miguel Ascencios
Randy Foehner
Richard Bennett
Brian Cox
Ron Klemetson
Andre Makovsky
Miles Sue
Bob Miyake
Ray Garcia
Leigh Rosenberg
Keith Warfield
Bob Rowley
Tom Spilker
Ted Sweetser
Dave Smith
Steve Wall

G&C
Mark Milman
Ed Wong
Fred Hadaegh
Guy Man
Randy Bartman
Ed Mettler
Chester Chu
Eldred Tubbs

AFF
Steve Lichten
Larry Young

INTERFEROMETRY
Jeff Yu
Mark Colavita
Jim McGuire

EO-1
Ron Boain

PPT
Joel Sercel
Juergen Mueller
Joe Cassady (OAC)

RF Modem
Faiza Lansing
Marty Herman